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INVESTIGATION OF RC BEAMS RETROFITTED WITH ULTRA HIGH STRENGTH CEMENTITIOUS COMPOSITE OVERLAY

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ABSTRACT

Studies have been carried out on flexural behavior of Reinforced Concrete beam retrofitted with Ultra High Strength Cementitious Composite (UHSCC) overlay. The dimensions of the Reinforced Concrete beam is kept as 1500 x 100 x 200mm. A Reinforced Concrete beam used for the study is considered control beam has been tested up to failure under four-point bending. Two RC beams have been preloaded up to 70% of the ultimate load and one RC beam has been preloaded up to 65% of ultimate load of control beam. The strengthening of preloaded RC beams have been carried out using UHSCC overlay, attached beneath the tension face of the preloaded beam. For 70% preloaded RC beam, the overlay is provided throughout the span of the beam whereas for the other 70% preloaded RC beam and the 65% preloaded RC beam, the overlay is provided only at the bending moment zone. During testing, the parameters such as load, deflection, cracks, failure pattern has been monitored. The numerical investigation has been carried out to validate the experimental results. This is done using FEA software ABAQUS. The cracks are modeled to show the preloaded effect for UHSCC strengthened RC beams and subsequently loaded as in real time, to estimate the increase in flexural strength of the beam. The results obtained from the experimental investigation and finite element analysis showed that the load carrying capacity and ductility are improved in the case of beams with UHSCC overlay when compared to conventional Reinforced Concrete beams thus finding its application in the retrofitting procedures.

Key words: Ultra High Strength Cementitious Composite, Strengthening, Overlay, Preloading

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1. INTRODUCTION

Concrete has been one of the most commonly used construction materials in the world. It is strong in compression but weak in tension. This reason paved the way for the introduction of Reinforced Concrete structures. Most of the infrastructure structures made up of Reinforced Concrete has been subjected to degradation due to corrosion, natural disasters, change in service load, error in the design, poor workmanship, etc. To improve the load carrying capacity of these damaged structure, retrofitting is the most widely used technique worldwide nowadays. There are many composite materials such as FRP, GFRP, External steel plates, etc that have been used for the purpose of retrofitting [1] [2]. But the FRP currently in use has some drawbacks like difficulty of application at low temperatures, moisture incompatibility, abrupt failure, emission of toxic fumes, etc. There were also considerable disadvantages in terms of huge cost of the methods and the skilled labors required.

To overcome these disadvantages, cementitious composites have come into prominence in this decade. The Ultra High Strength Cementitious Composite (UHSCC) consists of cementitious binders with steel fibers which provides greater degree of ductility and crack-width restricting property [3]. Hence this material can be used as an effective retrofit material.

In the present paper, The comparative study has been done on the flexural performance of convention RC beam and preloaded and UHSCC strengthened RC beam. Four point bending test have been carried out on all beams. The numerical investigation has been carried out to validate the experimental results.

2. ULTRA HIGH STRENGTH CEMENTITIOUS COMPOSITE

It consists of Portland cement, quartz powder, fine silica sand, high range of water reducer and small quantity of steel fibers. The absence of coarse aggregate improves the microstructure of the material. The presence of steel fibers enhances the strength and ductility of the composite. The material has the ability to deform and support flexural as well as tensile loads. These characteristics of UHSCC are the result of improved micro-structural properties of the mineral matrix and the control of bond between the matrix and fiber.

The mix ratio used was 1:0.25:1.1:0.4 (Cement: Silica fume: Quartz Sand: Quartz Powder). The percentage of steel fibers added to the dry binders was 1%. To improve the workability of the mix, super-plasticizer were added up to 3.5%. The water-cement ratio of the mix was lowered to 0.23 to increase the density of the mix. The dry binders were mixed thoroughly using Hobart mixer of 15kg capacity. Then the super-plasticizers and the water were added. The mixing was done till a slurry paste was formed which was followed by the addition of steel fibers.

The cementitious composite was allowed to cure for 28 days. It has a compressive strength of around 200MPa and the flexural strength of around 40MPa. The dimension of the UHSCC was kept as 100x10x1500mm.

3. EXPERIMENTAL INVESTIGATION

RC Beam

The dimensions of the Reinforced concrete beam was kept as 1500 x 100 x 200 mm^3. The grade of the concrete was M35 and the water cement ratio was maintained as 0.45. The mix proportion of the concrete beam was determined to be 1:1.669:1.856 according to IS 10262:2009 and IS 456:2000. The confinement to the beam was given as tension and compression reinforcements of 2-10mm diameter bars (Fe 415) as shown in figure 1. Clear cover was maintained as 25mm for the bottom reinforcements. To resist the shear forces, stirrups of 6mm diameter at 100mm centre to centre spacing were provided throughout the span of the beam.

The beam was cured for 28 days under water and the beam was white washed to detect the formation and the propagation of cracks while testing.

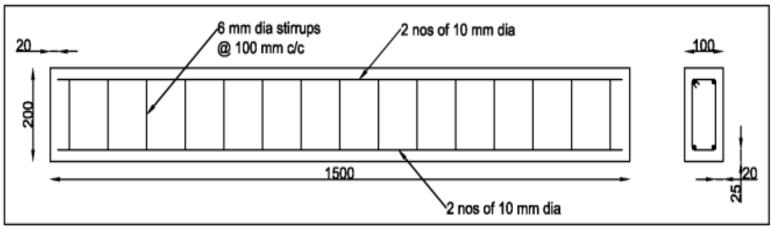


Figure 1 Reinforcement Detailing

Strengthened Beams

Three RC beams were preloaded to different degree of ultimate load and the length of the overlay for each strengthened beam was given in the Table 1.

BEAMS	LENGTH OF OVERLAY	PRELOADING EFFECT
RC_UHSCC1	800 mm	65% of ultimate load
RC_UHSCC2	700 mm	70% of ultimate load
RC_UHSCC3	1500 mm	70% of ultimate load

The strengthening was done using UHSCC, attached beneath the tension face of the damaged beam. The thickness of the overlay was kept as 10mm in all the beams. The bonding between the preloaded beams and the UHSCC layer was done using epoxy resin and their thickness was maintained as 3mm.

Testing Procedure

The beams (RC beam and the damaged RC beams strengthened with UHSCC overlay) were tested under four-point bending test as shown in figure 3. The experimental setup consists of a 500kN capacity servo hydraulic actuator with online data acquisition devices. The beams were tested using a displacement control testing machine with constant loading rate maintained at 0.5mm/min and the data was recorded using a 50Hz sampling rate. The effective span of the beam was kept as 1200mm and the end constraint was kept as a hinged on one end and roller on the other end(Simply Supported beam). The loading was applied at a distance of L/3 from the supports as shown in figure 2 on either side using steel cylindrical rollers. The monitoring devices used were Linear Voltage Displacement Transducers [LVDT's] and strain gauges to determine the deflection and strains of the specimens. The

strain gauges and LVDT were connected to the data analogue thereby connected to the system and hence the readings were stored.

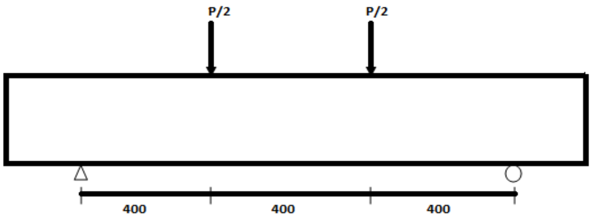


Figure 2 Loading Condition

Figure 3: Test Setup of Strengthened Beam

4. FAILURE MODES

RC_CON

The initial visible cracks were seen at the load of 24kN. The cracks were predominant in the constant bending moment zone shown in fig. The crushing occurs in the compression face of the beam after the tension steel yielded. The ultimate load taken by the beam was recorded as 72kN. The pattern of failure was by flexure as shown in Figure 4. No shear cracks and debonding were seen in the beam.

Figure 4 Flexural Failure of RC_CON in the bending moment zone

RC_UHSCC1

The visible cracks were initiated in the overlay material at a load of 24.5kN with dissipation of sound. The sound is due to the breaking of steel fibers in the overlay. The crack was seen in the constant bending moment zone of the overlay indicating the overlay material is failing in flexure. Till 54.5kN, the load was taken by the overlay material alone since no other cracks were seen propagating in the beam. The cracks started to widen in the overlay material after the load of 70kN is shown in Figure **5.** The steel reinforcements started to yield at a load of 65kN. The crushing of concrete occurred at the load of 79.5kN which is indicated by the

crushing of the top face of the concrete at the center of two loads. No predominant shear cracks or delamination phenomenon between the overlay and the beam material were found during testing.

Figure 5 Widening of Cracks in the Overlay

RC_UHSCC2

The visible cracks were seen in the overlay material at a load of about 21kN at the middle of the overlay. Shear cracks indicated by the diagonal cracks, were formed when the beam is loaded at 29kN. The sound was heard in the overlay material indicating the rupture of fiber in the overlay at a load of 30kN. There were three predominant cracks in the overlay formed in the constant bending zone of the overlay and was seen widening. The flexural cracks formed in the beam, before the initiation of experiment, started to propagate when the load was around 40kN. New flexural cracks were formed in the moment zone of the beam in addition to the older ones at a load of about 50kN as shown in figure 6. The shear cracks started to propagate towards the moment zone of the beam after beam was loaded at 66kN. The predominant cracks in the overlay stopped widening at the load of 57kN. After this load, the beam started to take up the load which is indicated by the propagation of shear cracks towards the moment zone. The cracks propagated to about 90% of depth of the beam. The crushing of concrete was visible at the load of 73kN which is indicated by the peeling of the top face of the concrete at the center of two loads.

Figure 6 Flexural Cracks in the Beam and the Overlay

RC_UHSCC3

The initial visible cracks started to appear at a load of about 20kN in the overlay material. There were four cracks formed in the constant bending moment zone of the overlay. The sound was continuously heard indicating the fibers would have yielded in the overlay material. The cracks formed in the beam started to widen in the beam portions after the load of about 45kN. New flexural cracks shown in figure 7 were formed at the bending moment zone of the beam in addition to that formed before initiation of the testing. Some hair line cracks were formed longitudinally in the beam at a load of about 75kN indicating that the beam was starting to experience debonding (between steel and the concrete). Shear cracks were seen during the end of testing. The de-lamination between the overlay material and the

beam were not seen after the testing. The crushing of concrete as shown in figure 7 occurred at the compression face of the beam. The ultimate load was recorded as 77kN.

Figure 7 Flexural Cracks & Crushing in the Beam

5. EXPERIMENTAL RESULTS

The load v/s deflection of the beams were compared as shown in figure 8. All the beams were tested by four point bending test under a constant displacement rate of 0.5mm/min. The following conclusions can be made from the experimental investigation which is also tabulated in the Table 2

- The ultimate load carrying capacity of all the preloaded strengthened RC beams is higher compared to control beam.
- The ultimate load carrying capacity of RC_UHSCC1 where strengthening is done only in the constant bending moment zone is approximately 11% higher compared to the control beam.
- The deflection corresponding to the ultimate load for all the beams is more or less same as that of the control beam.
- RC_UHSCC1[65% Preloading] has a higher load carrying capacity than RC_UHSCC2[70% Preloading] which indicates that the preloading effect influences the load carrying capacity of UHSCC strengthened RC beams.
- RC_UHSCC3 has a higher load carrying capacity compared to RC_UHSCC2 This indicates the length of the overlay is an influential factor in determining the load carrying capacity.
- The ductility of the preloaded UHSCC strengthened RC beams is found to be higher than the RC beam.

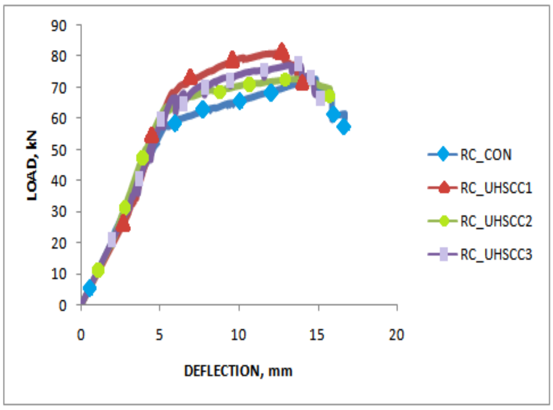


Figure 8 Load vs Deflection Plot

Beam	Ultimate Load, kN	Displacement at Ultimate Load, mm	% Increase In Load
RC_CON	72.739	14.39	-
RC_UHSCC1	81.042	12.437	11.414
RC_UHSCC2	72.893	13.457	0.211
RC_UHSCC3	77.081	13.897	7

6 NUMERICAL INVESTIGATION

Finite element failure analysis was performed to model the nonlinear behavior of the beams. The FEM package Abaqus/standard was used for analysis

7. MATERIAL PROPERTIES AND CONSTITUTIVE MODELS

Concrete

A plastic damage model was used to model the concrete behavior. This model assumes that the two main failure modes are tensile cracking and compressive crushing. The compressive strength f_{ck} was found to be 35 MPa. E_c and f_{cr} were then calculated by the formula

$E_c = 5000\sqrt{f_{ck}} = 29580.40$ MPa

$f_{cr} = 0.7\sqrt{f_{ck}} = 4.1428$ MPa

The poisson's ratio of the concrete was assmed to be 0.18. The stress-strain relationship in compression for concrete is given by Mander's model as shown in Figure 9.

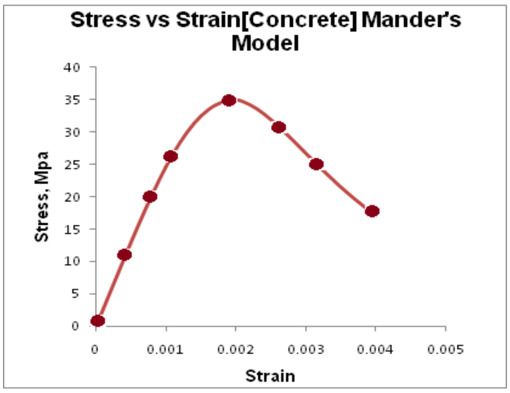


Figure 9 Stress-Strain relation of Concrete under uni-axial compression[Mander's Model]

Steel Reinforcement

The steel was assumed to be elasto-plastic material. The elastic modulus E_s and yield stress f_y were found to be 200GPa and 415 MPa. These values were used in the FEM model. A poisson's ratio of 0.3 was used for the steel reinforcement. To simulate the perfect bond, embedded regions were used between reinforcement and the concrete. The plastic properties of steel were provided based on the graph as shown in the Figure 10.

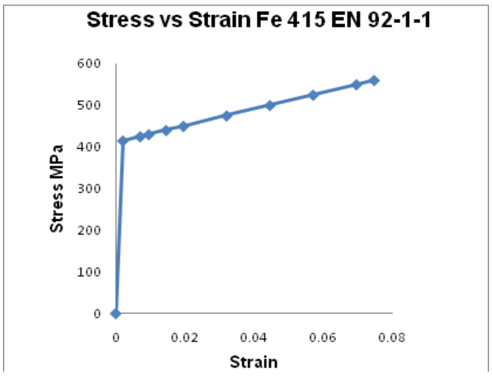


Figure 10. Stress-Strain behavior of steel

UHSCC

Since the overlay is attached beneath the tension face of the concrete, the tension in overlay will be predominant. Hence to predict the tensile behavior of the overlay, the tensile stress-strain values were provided as input as shown in Figure 11.

The young's modulus and the poisson's ratio was given as 45MPa and 0.24 respectively.

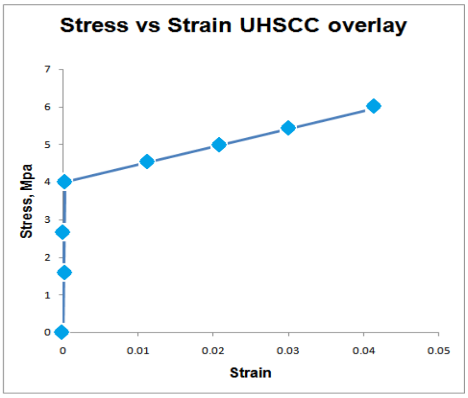


Figure 11 Stress-Strain of UHSCC under Tension

9. FINITE ELEMENT ANALYSIS

The concrete and the steel were modeled using a linear hexahedral element. This element has eight nodes with three degrees of freedom at each node–translation in the x, y, and z directions. The element used is capable of plastic deformation and cracking in three orthogonal directions. An eight node reduced-integration element was used to model the UHSCC. This element also has three degrees of freedom at each node. Eight-node 3-D cohesive elements were used to model the interface layer. Two interactions have been given, one is between the concrete and steel where embedded region was used and the other is between the concrete and ultra-high strength cementitious composite overlay in which a surface-surface contact was used. Abaqus/standard (Hibbitt, Karlsson, & Sorensen Inc. 2000) was used for these simulations. The preloading effect for the strengthened beams were simulated by inducing cracks in the bending moment zone of the control beams based on the preloading. The load increments were given based on the experimental investigation. The deflection contours for every beams were observed as shown in the figure 12.

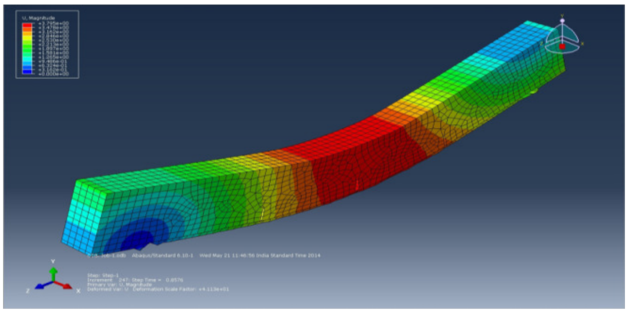


Figure 12 Deflection contour for a strengthened beam

10. VALIDATION OF NUMERICAL MODEL

The numerical model used for the parametric study was validated against the experimental results. There is a good correlation between the experimental results and the numerical results. In Figure 13, the load versus deflection curves at mid-span for the control beam as well as strengthened beams are shown. It is clear that there is only a slight deviation between experimental data and numerical results as evident from the Figures 14,15,16,17. The slight deviation is due to the fact that the assumption of perfect bond between steel and concrete elements make it a stiffer element. Hence, the proposed model proved to be able to simulate the composite behaviour of reinforced concrete beams retrofitted by UHSCC overlay successfully.

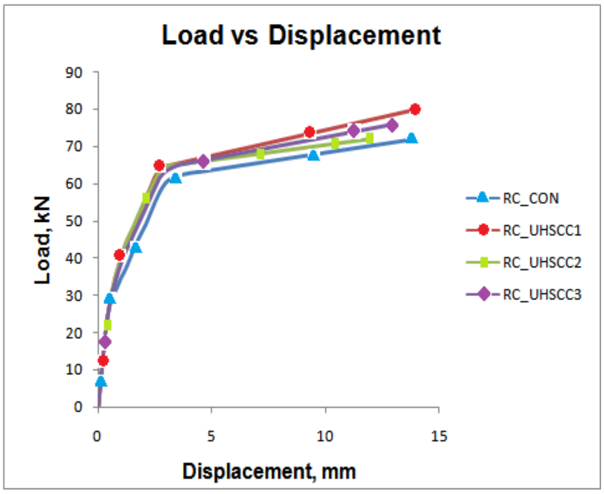


Figure 13 Load vs Displacement Plot

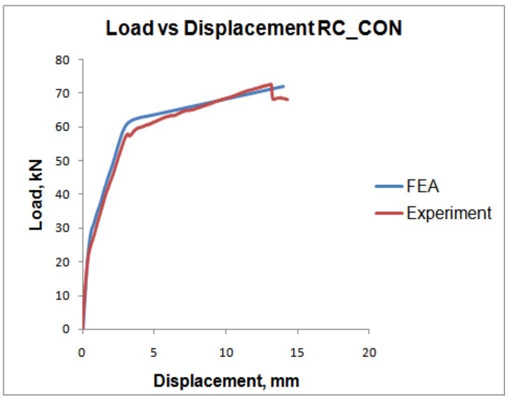


Figure 14 Load vs Deflection [RC_CON]

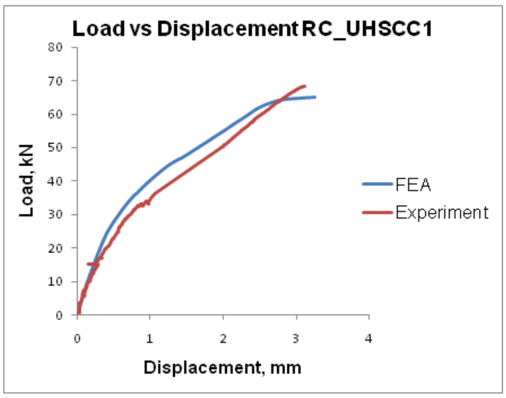
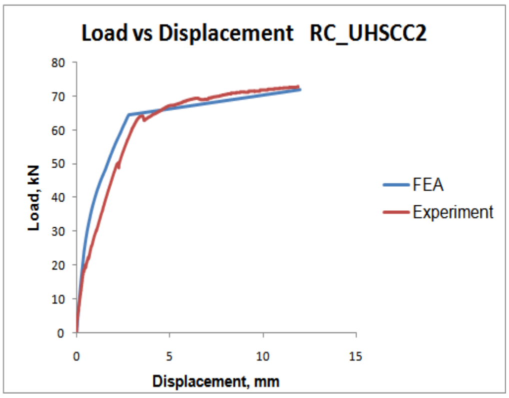


Figure 15 Load vs Deflection [RC_UHSCC1]



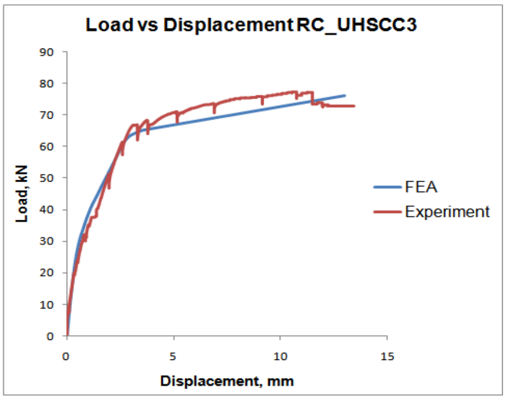


Figure 16 Load vs Deflection [RC_UHSCC2] **Figure 17** Load vs Deflection [RC_UHSCC3]

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